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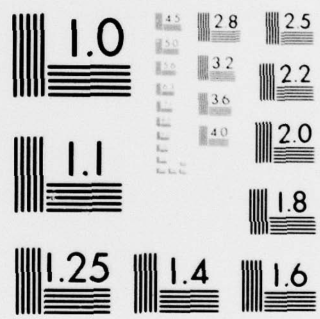

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TECHNICAL REPORT T-79-69

LASER INTRACAVITY MODULATION AND STABILIZATION

Richard A. Curtis
Technology Laboratory

May 1979

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The description of a method of generating optical-frequency sensitive signals in single mode lasers is presented in this report. The technique involves controlled coupling of energy from the optical mode having gain to other laser cavity resonances using an intracavity phase modulator. The theory which applies to this work was obtained from the coupled mode equations of Harris and McDuff and is based on single mode laser stabilization theory of McDuff and Curtis. Experiments were performed which verified the theory using a single mode, carbon dioxide laser and a cadmium telluride (CdTe) electro-optic modulator.

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20. A closed loop control system was constructed which was similar to that used by Targ, Osterink and French with a multimode, Helium-neon laser.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the aid of Messr. G. Rast and Sobiesky through their helpful suggestion and loans of equipment.

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CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

Although it is much more coherent than usual light sources, when studied in detail a normal gas laser is discovered to radiate with somewhat erratic power and frequency variations. Under proper conditions, self locking may occur in multimode lasers which temporarily stabilizes the average output power, but this effect is unpredictable and not suitable for experiments in which relatively precise coherence is desired.[1] A method which has been explored for stabilizing multimode gas lasers utilizes an FM modulation produced signal in the laser output to stabilize the power and frequency of the set of laser modes.[2] The single mode laser has been shown theoretically to have a similar modulation produced signal under proper conditions.[3]

The modulation scheme which is the subject of this work is the well known one in which an electro-optic modulator is placed inside the optical cavity and driven by an applied voltage at a frequency which depends on the cavity dimensions, as in the usual mode-coupling procedure. The modulator changes the effective cavity length. An equivalent but less practical scheme at the present state of the art is to physically move one of the cavity mirrors longitudinally at the same frequency.[4] This effective cavity length variation is termed phase modulation.

The following section contains the theory which shows how the frequency-sensitive signal is produced in a single mode laser. After that the experimental demonstration of the use of this signal to stabilize a carbon dioxide laser is reported.

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1. P. W. Smith, "Mode-Locking of Lasers," *Proceedings of the Institute of Electrical and Electronic Engineers*, Vol. 58, September 1970, pp. 1342-1347.

2. R. Targ, L. M. Osterink, and J. M. French, "Frequency Stabilization of the FM Laser," *Proceedings of the Institute of Electrical and Electronic Engineers*, Vol. 55, July 1962, pp. 1185-1192.

3. R. A. Curtis and O. P. McDuff, "Stabilization of Single Mode Lasers Using Intracavity Phase Modulation," *Program of the International Electron Devices Meeting*, December 1975, pp. 611-614.

4. O. P. McDuff and A. L. Pardue, Jr., "Theory of Mode-Coupling in the Length Modulated Laser," Presented at the 1967 International Electron Devices Meeting, October, 1967.

2. COUPLED MODE THEORY

A. THE COUPLED DIFFERENTIAL EQUATIONS

A set of equations used to describe an intracavity phase modulated laser were derived by Harris and McDuff.[5] These equations include the effects of atomic lineshape, gain saturation, detuning of the modulator and the dispersion effects of the active medium. They were derived from the self-consistency equations of Lamb, which were in turn obtained from a wave equation and harmonic oscillator approach to the relationship between the electromagnetic fields and the polarization of the laser medium[6]. The Harris and McDuff equations which describe the phase modulated system are

$$[\dot{\phi}_n - n\Delta\nu + \frac{c}{2L}\Psi_n]E_n = -\frac{\delta_c c}{2L}[E_{n+1}\cos(\phi_{n+1} - \phi_n) + E_{n-1}\cos(\phi_n - \phi_{n-1})] \quad (1)$$

and

$$\dot{E}_n + \frac{c}{2L}(\alpha_n - G_n)E_n = \frac{\delta_c c}{2L}[E_{n+1}\sin(\phi_{n+1} - \phi_n) - E_{n-1}\sin(\phi_n - \phi_{n-1})] \quad (2)$$

In these equations the dot above a term is the standard representation for a time derivative and the subscript n is an identification of a particular laser cavity oscillation frequency, where $n = 0$ is that a frequency closest to the center of the atomic line. Values of n greater than zero designate those laser modes (frequencies) higher in frequency and values of n less than zero designate modes lower in frequency than the $n = 0$ mode. The terms in the equations are E_n and ϕ_n which represent the slowly time varying amplitude and phase, respectively, of the nth cavity mode; $\Delta\nu$ which represents the detuning of the modulator drive with respect to the cavity mode spacing frequency, $\frac{c}{2L}$, where c is the velocity of light and L is the laser cavity length; ψ_n which represents the dispersion of the active medium; δ_c which represents the phase retardation per pass seen by the optical field in the modulator; α_n which represents the optical losses including output coupling which affect the nth mode; and G_n which represents the unsaturated gain of the laser medium at the nth mode frequency.

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5. S. E. Harris and O. P. McDuff, "Theory of FM Laser Oscillation," *Institute of Electrical and Electronic Engineers Journal of Quantum Electronics*, Vol QE-1, September 1967, pp. 245-262.

6. W. E. Lamb, Jr., "Theory of an Optical Laser," *Physical Review*, Vol. 134, June 1964, pp. A1429-1450.

When Equations 1 and 2 are solved they give the mode amplitudes and phases for a given set of conditions. These mode amplitudes and phases may then be used to find the particular property of the optical output signal which is desired. Choosing conditions which correspond to those of a single mode laser, so that only one cavity oscillation frequency is capable of lasing independently, the numerical solution of Equations 1 and 2 was accomplished by a fourth-order Runge-Kutta approach.

B. LASER INTENSITY EQUATION

To study the mode-frequency-sensitive signal, further calculations are necessary. An equation which gives the amplitude and time-dependence of the laser output intensity, when the laser mode amplitudes and phases are known, is

$$W(t) = \frac{1}{2} \sum_s \sum_n E_n E_{n+s} \cos (s \nu_m t + \phi_{n+s} - \phi_n), \tag{3}$$

where W(t) is the envelope of laser intensity as a function of time and ν_m is the radian frequency of the modulator drive signal.[6] This equation represents the summation of radio frequency signals which would result from the square law detection of the laser output if the incident radiation were given by an expression of the form

$$E(t) = \sum_n E_n \cos [(\Omega_o + n \nu_m) t + \phi_n], \tag{4}$$

where Ω_o is the optical frequency of the mode which has gain.

C. OPTICAL FREQUENCY SENSITIVE SIGNAL

The signal of interest is given by Equation 3 with s = 1. The resulting equation gives the amplitude of that component of the laser output frequency which is at the modulator frequency, ν_m.

$$W_1(t) = \frac{1}{2} \sum_n E_n E_{n+1} \cos (\nu_m t + \phi_{n+1} - \phi_n). \tag{5}$$

When this equation is evaluated for the calculated mode amplitudes and phases corresponding to different frequency positions of the modes, the result shown in *Figure 1* is obtained.

The curve shown in *Figure 1* is the result of Equation 5 for mode shifting. The sharp null which occurs in the curve occurs at zero shift where the mode which has gain is at line center.

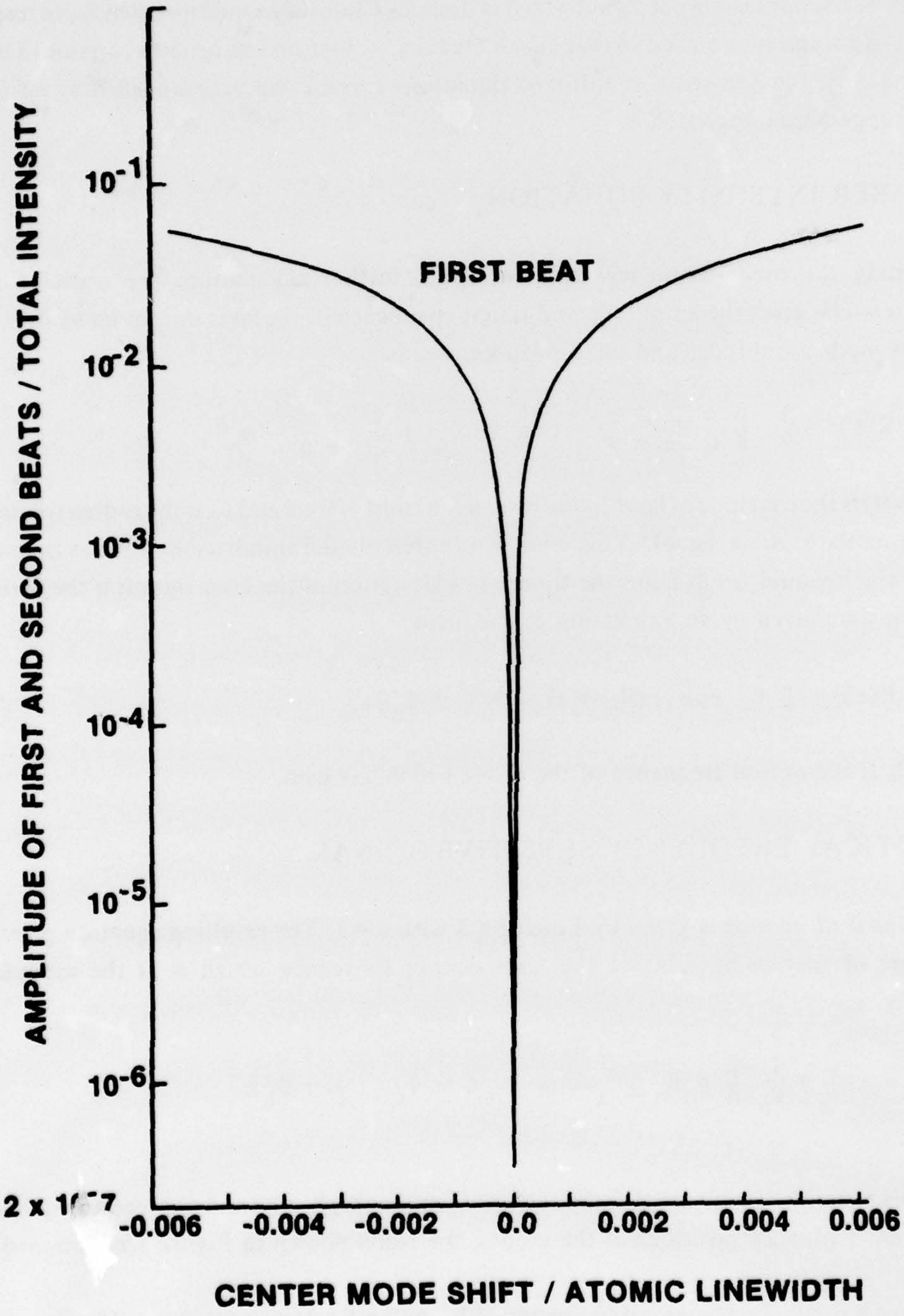


Figure 1. Normalized first beat for center mode shift.

When this occurs, the permittivity experienced by the zeroth mode is the same as that of the other modes which are coupled to it by the modulator. Physically, the conditions are such that the beat between the $n = 0$ and $n = 1$ modes destructively interferes with the beat between the $n = 0$ and $n = -1$ modes, and so forth for symmetrically coupled laser modes. When the zeroth mode moves off line center, the dispersion of the active laser medium changes the permittivity seen by the zeroth mode, shifting its phase and preventing the destructive interference present previously. The resulting beat signal grows in amplitude with large amounts of mode shifting until the laser output is predominantly varying at the first beat frequency, i.e., the first beat component becomes large.

The characteristics of the curve in *Figure 1* indicate that the signal could be used to determine when the mode having gain is at line center, to within about 0.5 percent of the atomic linewidth. If a system were devised to position one of the laser cavity mirrors in response to this null, the output could be stabilized in frequency and power. This is the result which has been accomplished.

3. EXPERIMENTS AND RESULTS

This section contains a description of the more important experiments performed in this research. The tests of the phase modulator are first described, then followed by tests of the modulation effects on the laser output. Finally, the laser stabilization equipment is tested and some of its characteristics are measured.

A. MODULATOR TESTS

The laser modulator crystal was a cadmium telluride (CdTe) material which had a 0.5 x 0.5 cm square cross-section with a length of 5 cm. The crystal was electrically part of a variable tuned circuit which could be adjusted for drive frequencies between 88 and 104 MHz by means of a trimmer capacitor. This frequency adjustment was made by setting the capacitor so that no energy was reflected from the modulator when measured with a bi-directional power monitor.

The first experiment with the modulator was to determine the maximum modulation depth or phase coupling that could be expected with the planned modulator drive. This was done using a standard technique (Heard) as shown in *Figure 2*.

The modulator was first tuned to 96 MHz and the driver oscillator and amplifier left at that frequency. This modulation was observed by the detector and oscilloscope by applying

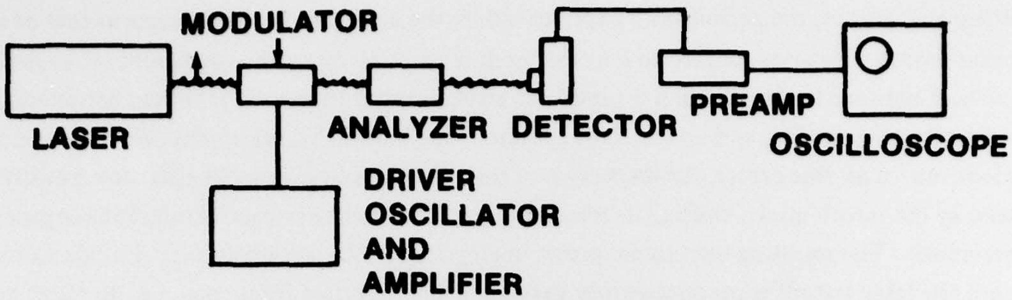


Figure 2. Apparatus for tests of modulator phase retardation.

internal amplitude modulation at 1.0 kHz in the oscillator. An 86% depth of modulation was selected.

Optically, the technique works by orienting the analyzer such that a minimum of the polarized laser light is transmitted to the detector. The effect of the modulator is then to rotate the laser light polarization such that more light is transmitted through the analyzer in proportion to the voltage applied to the modulator. The analyzer was tested and found to be 98% efficient in blocking the laser light without the modulator.

In the experiment, the modulator was driven with about 4.67 W of r-f signal which was the maximum that could be obtained into the matched load. The signal received by the oscilloscope is shown in *Figure 3*. Using the standard formula it was found that a phase coupling, $\delta_c = 0.16$

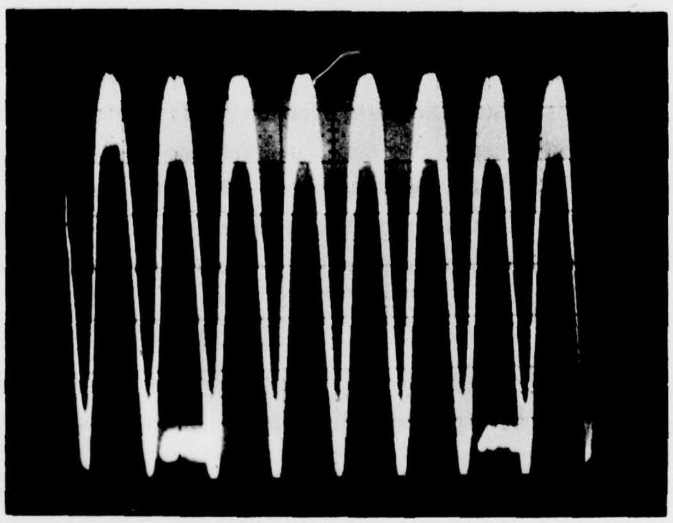


Figure 3. Modulator phase retardation measurement signal.

could be obtained. It is expected from theory that this value should be sufficient for the stabilization desired.

The next test of the modulator was to attempt to couple laser modes and produce pulsing of the laser output. The modulator was mounted in the laser cavity next to one mirror as shown in *Figure 4*. The experiment was run with the apparatus shown in *Figure 5*. Since theory says that the pulsing should occur at either the rate of the modulation frequency or twice the modulation frequency with a pulse width of about ten nsec it would not be possible to directly observe the laser pulses with our present detector. What was done was to observe the fundamental beat at the modulator frequency with a wide bandwidth oscilloscope.

First, The apparatus was set up as shown in *Figure 6*. The modulator drive frequency was adjusted as closely as possible to an optimal coupling frequency.

The laser output with modulation was about 2.0 W average. The modulator was driven with 3.0 W at 97.437 MHz. The detected signal was preamplified between 1.0 kHz and 150 MHz at a gain of 40 dB. The oscilloscope had a 100 MHz bandwidth.

The laser cavity length was controlled by adjusting the voltage to a piezoelectric translator (PZT). This was done to see what changes in the detected signal could be observed. It was expected that the modulator frequency signal should be a minimum or null when the laser mode having gain is at line center frequency.

The results of this experiment are shown in *Figure 7a* and *7b*. It was observed that the relatively strong signal of *Figure 7a* was obtained which had a strength dependence on the laser cavity length. The minimum signal of *Figure 7b* was obtained in small ranges of PZT voltage.

B. MEASURE OF FIRST BEAT SIGNAL AMPLITUDE WITH MODE SHIFTING

The next step in developing the control system was to attempt to observe an error signal which has the characteristics of the first beat with changes in the laser cavity length. (See Theory Section) This was done using the apparatus shown in *Figure 8*.

A ramp voltage generator was used to drive the PZT with time to produce a little more than one cavity mode spacing sweep of the laser signals through the atomic line frequency range. This adjustment was made based on separate experiments with the laser and the PZT.

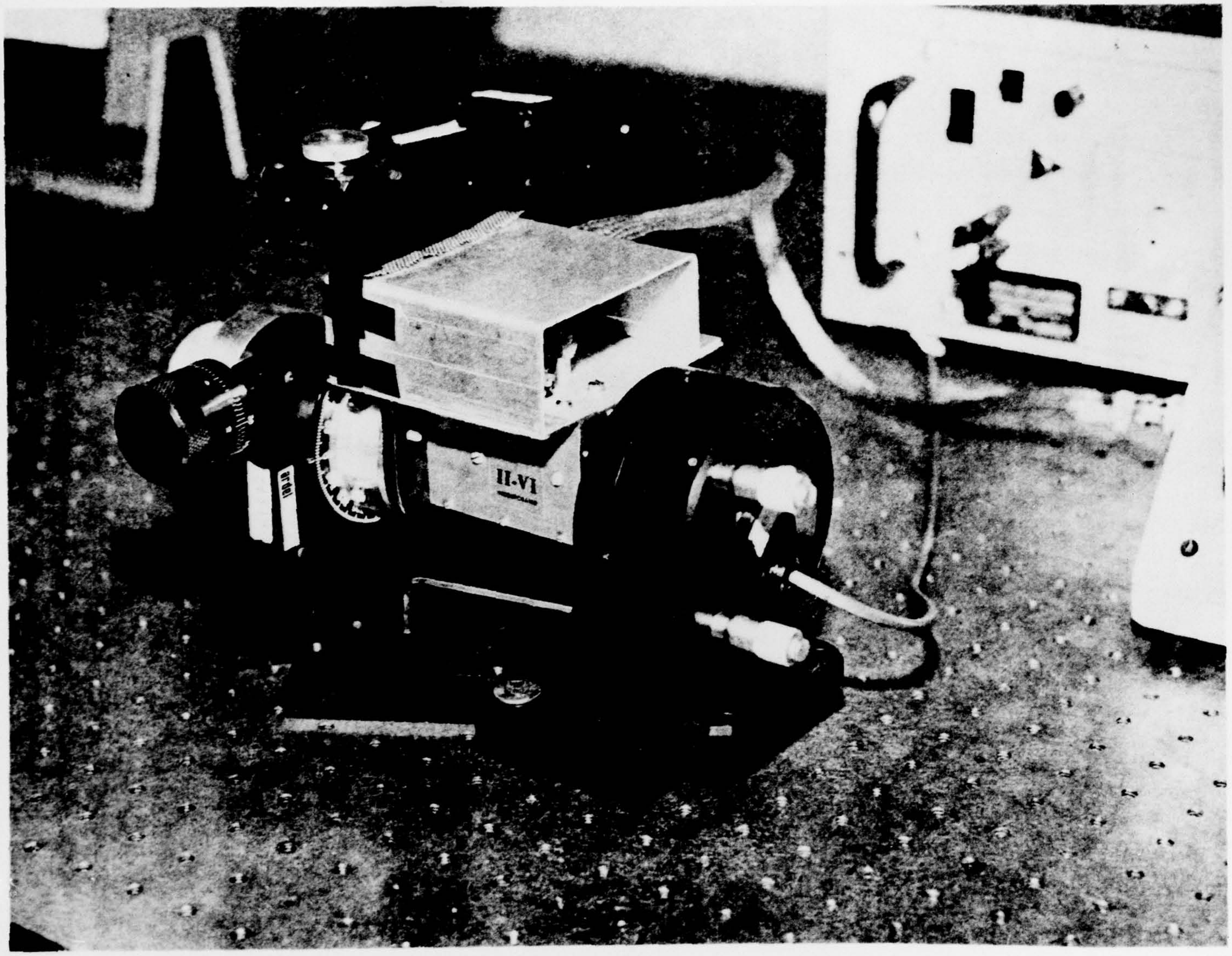


Figure 4. Modulator in six degree-of-freedom mount next to translating (PZT) mirror.

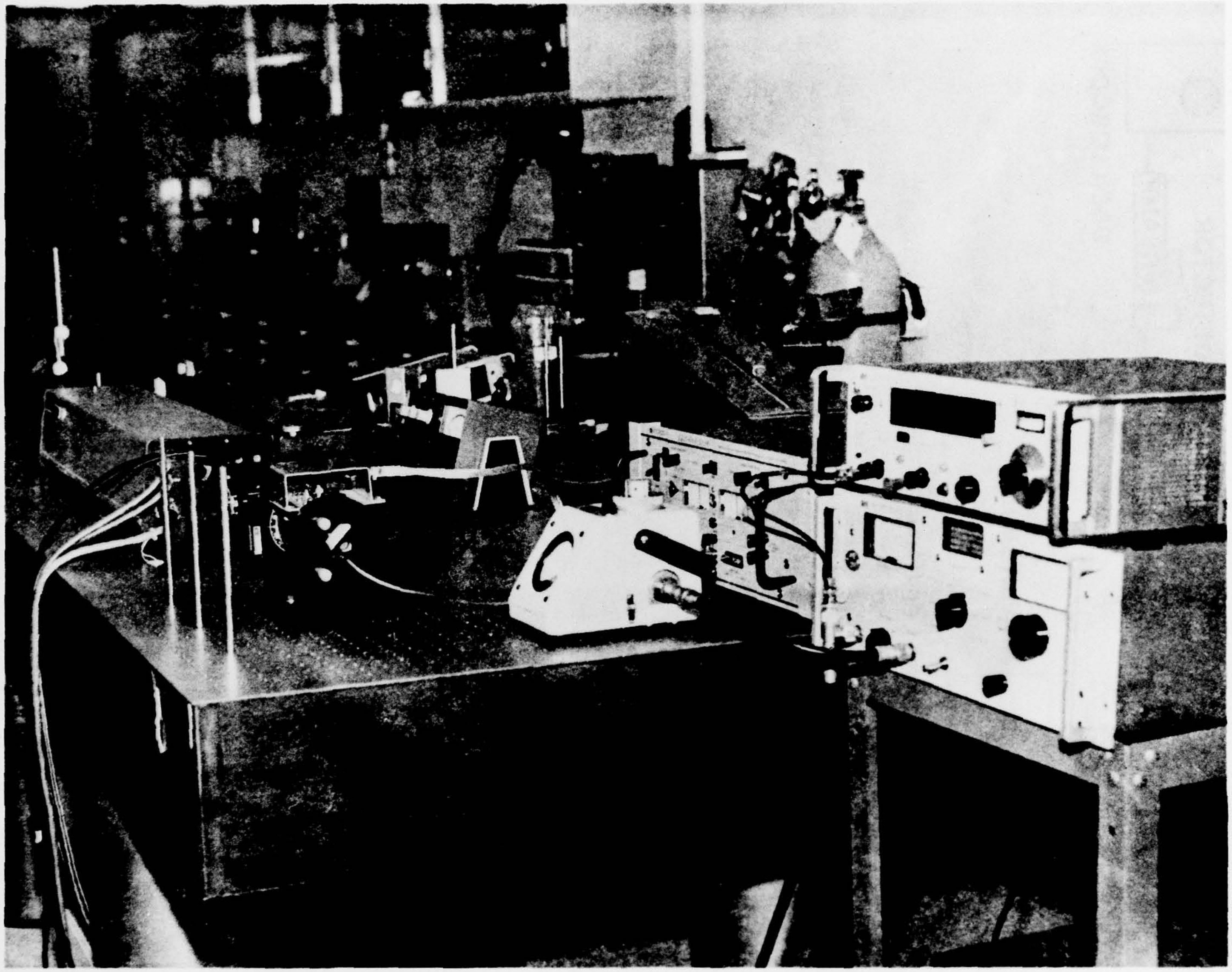


Figure 5. Laboratory apparatus for initial modulation test.

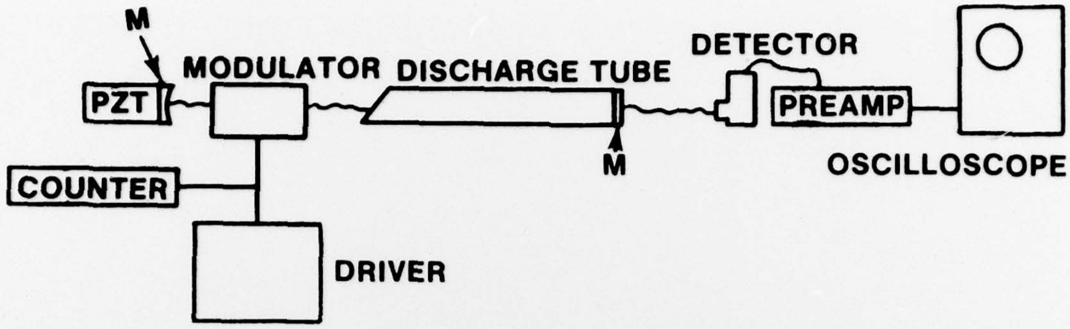
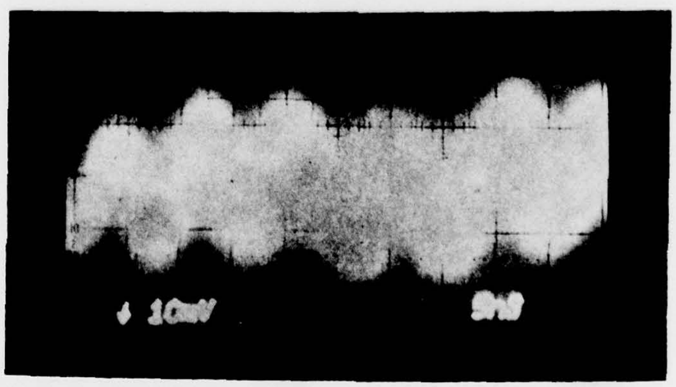


Figure 6. Apparatus for observing mode coupling.

(a) Strongest signal at the modulator frequency.



(b) Weakest signal at the modulator frequency.

Figure 7. Signals detected in the laser output as a function of laser cavity length.

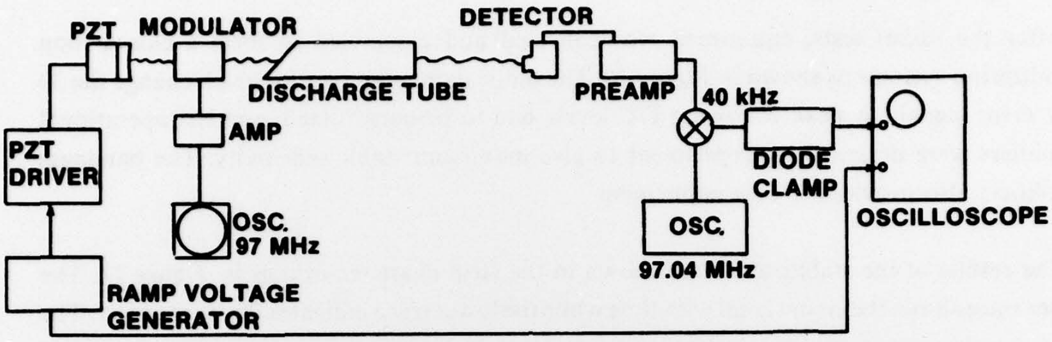


Figure 8. Apparatus for observation of an error signal.

The signal observed on the oscilloscope was the peak amplitude of the 40 kHz beat between the detected laser pulsing fundamental frequency and a reference oscillator which was adjusted for the 40 kHz difference frequency. This signal is shown in *Figure 9*. The straight line is the ramp voltage used to control the PZT driver.

These data show that for a change in laser frequency (from PZT drive voltage changes) of about 2.4 MHz, the error signal changes by about 10 dB in voltage from its minimum level. Although this is not a direct measure of the first beat signal it is in good agreement with predicted performance.

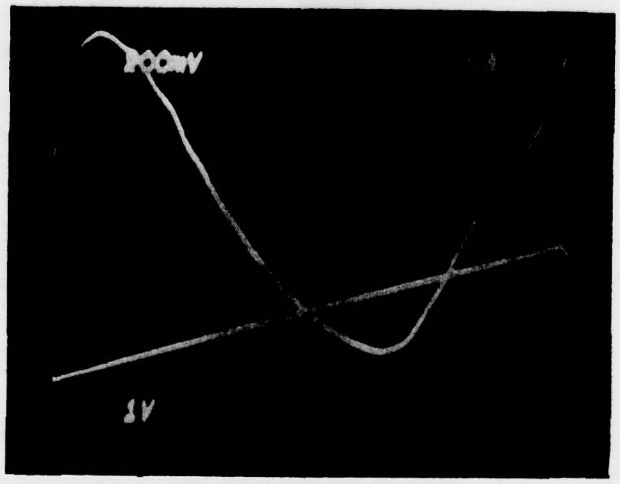


Figure 9. Modulation produced error signal.

4. CONTROL SYSTEM EXPERIMENTS AND RESULTS

After the initial tests, equipment was collected and assembled to form a closed loop stabilization systems as shown in *Figure 10.* The diode damper networks which change the 30 kHz error signals to peak following DC levels had to be constructed, and the operational amplifiers were designed by experiment to give maximum stable sensitivity. The bandpass amplifiers also provided a gain adjustment.

The results of the stabilization are shown in the strip chart recordings in *Figure 11.* The upper trace shows the error signal with time while the lower trace indicates the laser power. The sharp break occurs when the control loop is turned off, leaving the error signal at zero level. The striking difference in laser power stability is obvious.

Further data shown in *Figure 12* demonstrate the effects of turning off the control and turning it back on after a significant delay. The system was turned off in each case by turning off the modulation.

These data show that the laser power was stabilized by the system to within ±3% worst-case with most of the stabilization holding the output power to within ±2%. This is a marked contrast to the ±30% stability of the free-running laser under the same conditions.

Another experiment was run to check the range of the modulator frequency which could be used to operate the control system. It was found that the system operated for modulation frequencies over the full range of load matching available (88 to 104 MHz). This is different from the theory[3] but is probably due to the laser stabilizing on different laser lines.

5. CONCLUSIONS AND RECOMMENDATIONS

It has been clearly shown that the proposed intracavity modulation system for laser stabilization provides a significant improvement in power stability over a "thermally stabilized" free-running laser. This system would be useful wherever a constant-power laser source is important.

There are still details of the laser transition and wavelength control which were not investigated. These points could be objects of useful follow-up research. However, it is felt that the most important aspects of the research are complete.

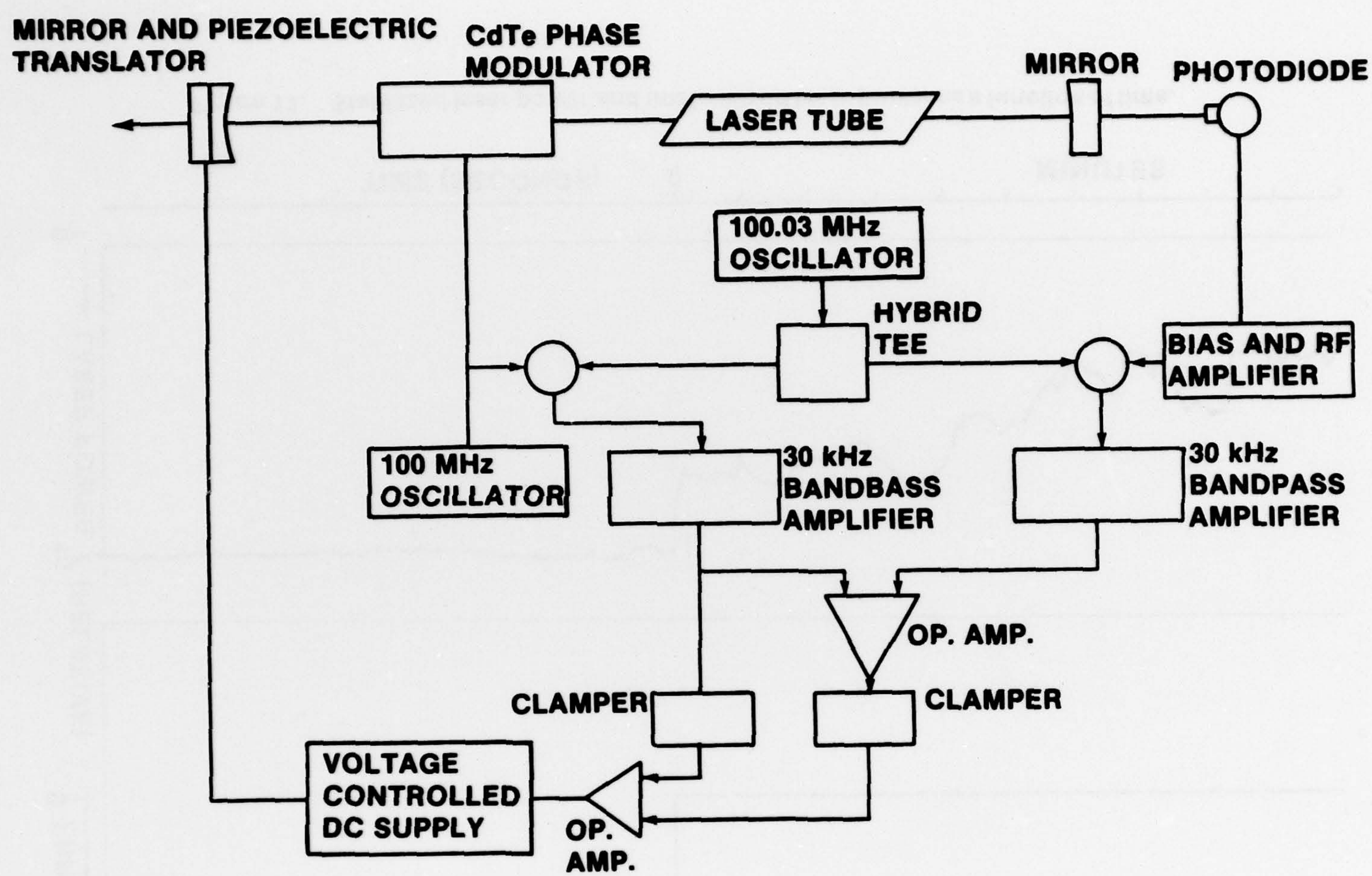


Figure 10. Completed laser cavity length control system.

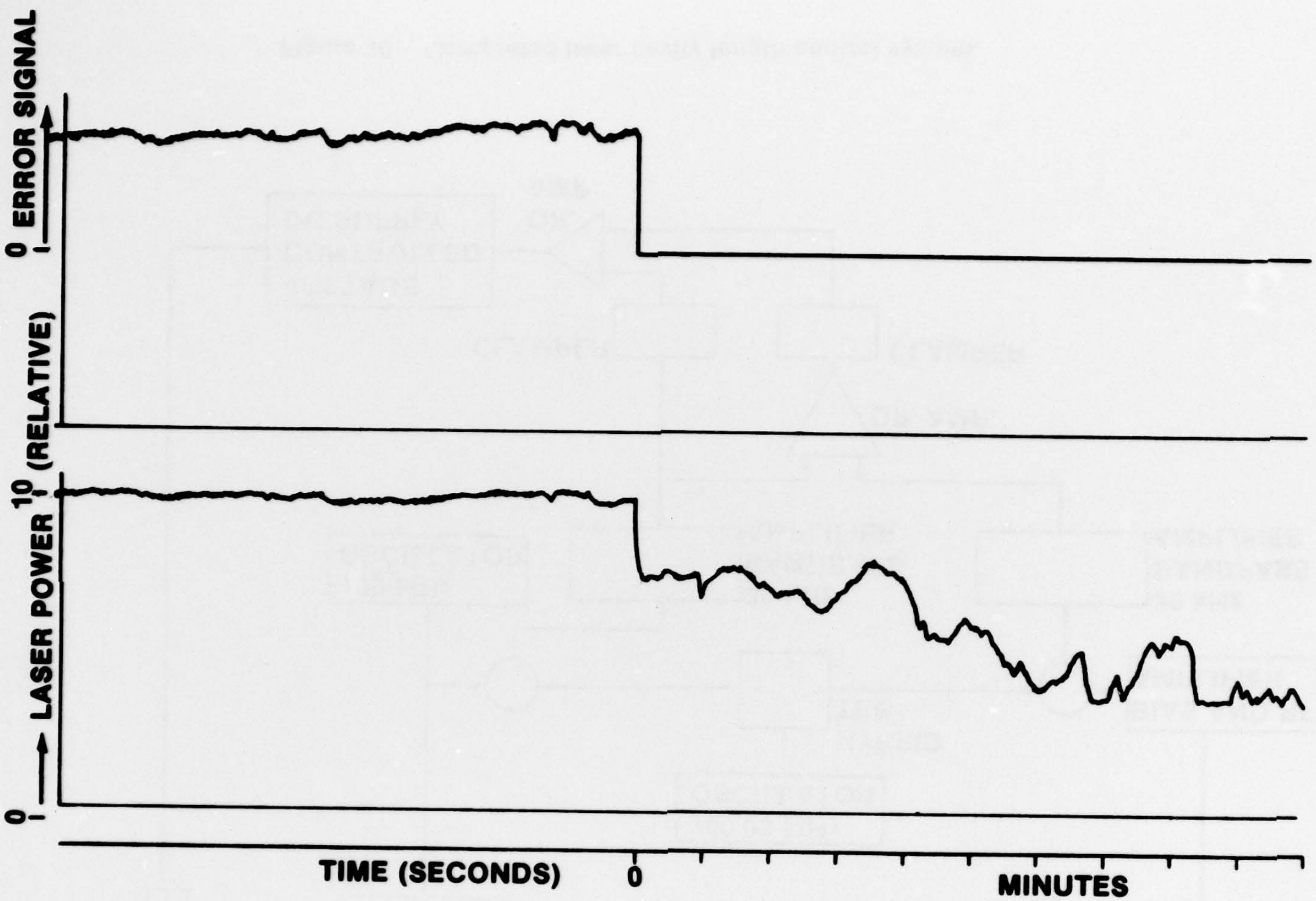


Figure 11. Stabilized laser power and unstabilized laser power as a function of time.

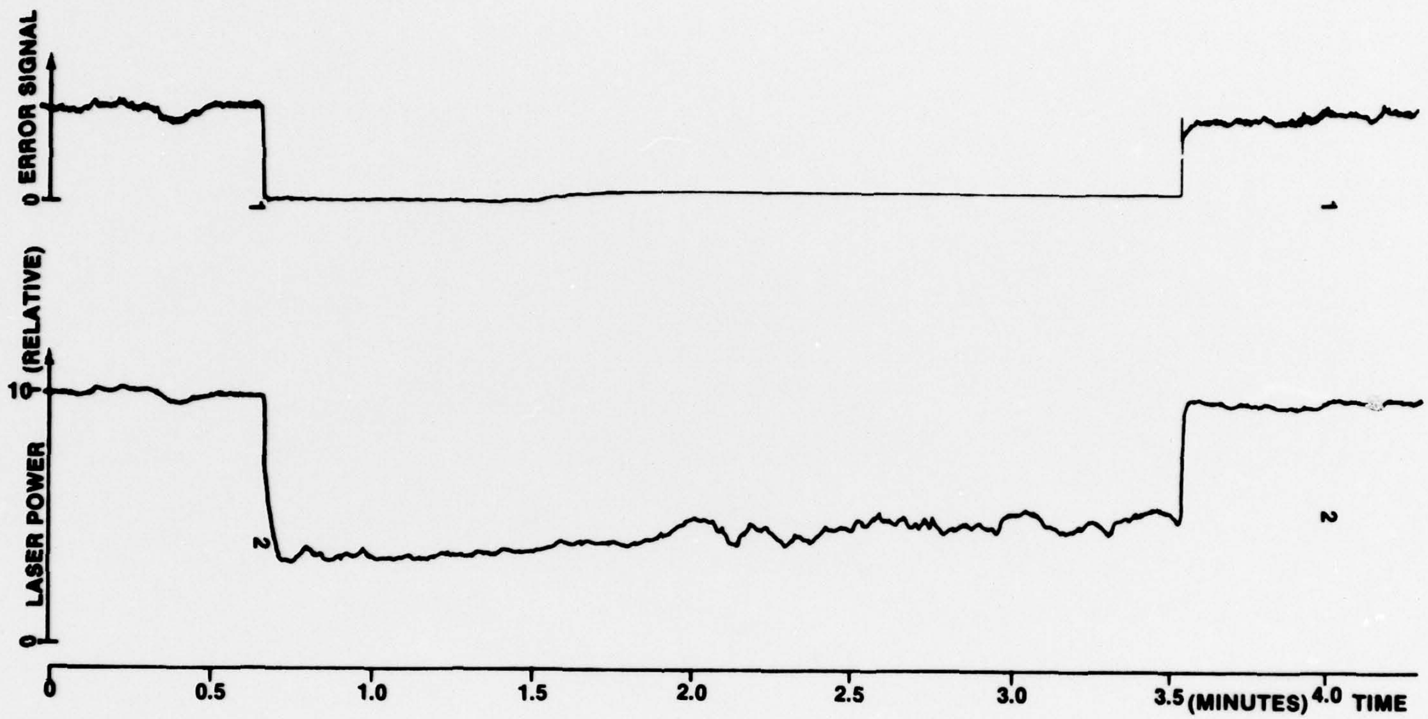


Figure 12. Laser power characteristics stabilized/unstabilized/stabilized.

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1. Smith, P. W., "Mode-Locking of Lasers," *Proceedings of Institute of Electronic and Electrical Engineers*, Vol. 58, September 1970, pp. 1342-1347.

2. Targ, R.; Osterink, L. M. and French, J. M., "Frequency Stabilization of the FM Laser," *Proceedings of Institute of Electronic and Electrical Engineers*, Vol. 55, July 1962, pp. 1185-1192.

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